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THE DEVELOPMENT OF SOME KINDS OF LRS INJECTORS

by

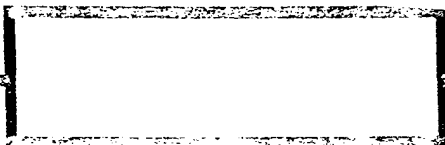
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Yu Yueying

## ABSTRACT

This article introduces technical problems which appear in the development of several types of liquid rocket engine injectors and ways to solve them. At the same time, analysis was done of dual component centrifugal type injector nozzle flow amount deviations. Inquiries were made into methods of controlling flow amount deviations. A type of body interior cooling system was put forward. Option was made for the use of beveled slot drill rod welded integral type structures. In medium thrust liquid rocket engines, experiments were carried out and preliminary conclusions obtained.

KEYWORDS Liquid rocket engine, Injector, Cooling System, Film cooling

## 1 TWO TYPES OF INJECTOR HEADS ON CERTAIN AIR-GROUND ENGINES

As far as single component centrifugal type injector heads on certain models of liquid rocket engines are concerned, 138 oxidizer and 85 combustion agent spray nozzles present a honeycomb sort of arrangement. Due to the fact that residual oxygen coefficients in head side areas are not uniform, it is not possible to form reliable low temperature fluid film cooling layers required for cooling chamber walls. During development, there was the appearance of combustion chamber throat section ablative phenomena. As far as relevant development and production plants are concerned, although they have opted for the use of such plans as adjusting side area residual oxygen /16 coefficients, and so on, they have all, however, still not proven effective.

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\* Numbers in margins indicate foreign pagination.  
Commas in numbers indicate decimals.

In the same models as above, option is made for a different type of 85 dual component centrifugal injector nozzle concentric circular arrangement forming head injectors for development, and it achieved success.

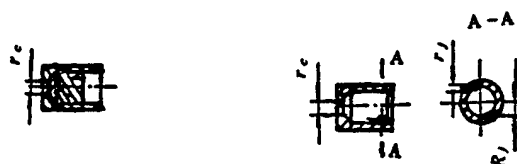
Going through large amounts of surface heat test run data statistics, engines with improved heads--as compared to unimproved ones--raised thrusts  $21\text{N}\cdot\text{s}/\text{kg}$ . Injector heads formed from 223 individual component spray nozzles were changed into heads formed from 85 dual component centrifugal type spray nozzles. After that, not only was engine performance increased, but--what was even more striking--engine operating reliability problems were resolved. Throat sections did not produce ablation any more. At the same time, following along with this, because of the advantages of changing spray nozzle forms and reducing the number of spray nozzles, as a result, structures were simplified, man hours were saved, and engine structure weights were lightened 3kg.

The two cases above show the different results produced by different types of injector head structural arrangements and atomization mixture component--spray nozzle structures. Dual component centrifugal type spray nozzles possess outstanding advantages in atomization mixing homogeneity. In the process of developing the types of spray nozzles in question, we did some work in the area of how to control spray nozzle flow amount variations.

## 2 CENTRIFUGAL TYPE SPRAY NOZZLE FLOW AMOUNT VARIATIONS AND THEIR CONTROL

Centrifugal type spray nozzles (Fig.1)--according to fluid rotation forms--can be divided into tangent direction types and types having vortex devices. As far as the relatively numerous

influences on centrifugal type spray nozzle flow amounts are concerned, it is only when the key factors have been analyzed that it is possible to apply effective controls.



Vortex Device

Tangent Apertures

Fig. 1

## 2.1 Centrifugal Type Spray Nozzle Flow Deviations

Opting for the use of small deviation methods [1], flow amount deviation and parameter change relationships are specified.

The flow amount formula is:

$$G = \mu \pi r_c^2 \sqrt{2g\gamma \Delta p} \quad (1)$$

In the equation,

$G$ --spray nozzle flow amount	$\mu$ --spray nozzle flow amount coefficient
$r_c$ --exit aperture radius	$\Delta p$ --spray nozzle pressure drop
$\gamma$ --fluid density.	

After differentiating by equation (1), one obtains:

$$\frac{dG}{G} = \frac{d\mu}{\mu} + 2 \frac{dr_c}{r_c} + \frac{1}{2} \left( \frac{d\gamma}{\gamma} + \frac{d\Delta p}{\Delta p} \right) \quad (2)$$

The relationship between flow amount coefficient  $\mu$  and spray nozzle effective cross section coefficient  $\varphi$  is:

$$\mu = \varphi \sqrt{\frac{\varphi}{2 - \varphi}} \quad (4)$$

Along with this, the expression relating spray nozzle geometric characteristic  $A$  and spray nozzle effective cross section coefficient  $\varphi$  is:

$$A = \frac{\sqrt{2} (1 - \varphi)}{\varphi \sqrt{\varphi}} \quad (4)$$

Also,

$$A = \frac{R_j r_c}{i r_j^2} \quad (5)$$

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In the equations,  $R_j$  — vortex flow chamber radius,  $r_j$  — spray nozzle entry radius,  $i$  — spray nozzle entry aperture number and vortex device spiral number.

After going through simplification of the various forms above:

$$\frac{d\mu}{\mu} = \frac{-2(1-\varphi)}{2-\varphi} \left( \frac{dR_j}{R_j} + \frac{dr_c}{r_c} - 2 \frac{dr_j}{r_j} \right) \quad (6)$$

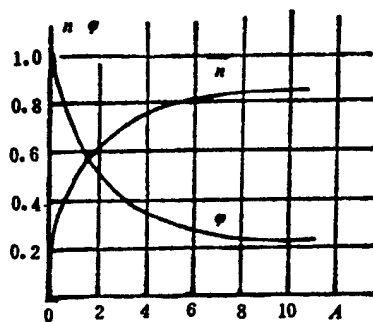
Let

$$n = \frac{2(1-\varphi)}{2-\varphi} \quad (7)$$

Then, equation (6) is changed to become:

$$\frac{d\mu}{\mu} = -n \left( \frac{dR_j}{R_j} + \frac{dr_c}{r_c} - 2 \frac{dr_j}{r_j} \right) \quad (8)$$

Fig.2  $n=f(A)$  Curves



Substituting equation (8) into equation (2), after simplification, one gets a form representing centrifugal type spray nozzle flow amount deviations:

$$\frac{dG}{G} = (2-n)\frac{dr_c}{r_c} + 2n\frac{dr_i}{r_i} - n\frac{dR_i}{R_i} + \frac{1}{2}\left(\frac{d\gamma}{\gamma} + \frac{d\Delta p}{\Delta p}\right) \quad (9)$$

Making use of  $n=f(\varphi)$  and  $A=f(\varphi)$  function relationships, one does up the curves between  $n$ ,  $A$ , and  $\varphi$ . See Fig. 2. Using small deviation methods to express (9), it is possible to write it as:

$$\delta G = (2-n)\delta r_c + 2n\delta r_i - n\delta R_i + \frac{1}{2}(\delta\gamma + \delta\Delta p) \quad (10)$$

## 2.2 Key Factors Influencing Spray Nozzle Flow Amount Deviations

Use is made of equation (10) in order to analyze factors influencing spray nozzle flow amount changes associated with relative deviations in various parameters.

### 2.2.1 Influences of Spray Nozzle Entry and Exit Aperture Dimension Relative Deviations on Spray Nozzle Flow Amounts

When  $r_j$ ,  $R_j$ ,  $\gamma$ ,  $\Delta p$  are constants, if  $\delta r_c$  increases 1%, then, spray nozzle flow amounts increase  $(2-n)\%$ .

When  $r_c$ ,  $R_j$ ,  $\gamma$ ,  $\Delta p$  are constants, if  $\delta r_i$  increases 1%, then, spray nozzle flow amounts increase  $2n\%$ .

At the same time, when  $\gamma$ ,  $\Delta p$  are constants, and spray nozzle geometrical characteristics  $A$  are different, following along with changes in spray nozzle effective cross section coefficients, magnitudes of spray nozzle flow amount changes are different. For

example, When  $A=2$ , from  $n=f(A)$  curves, it is possible to find that  $n = 0.697$ . At this time, one has:

$$\delta G = 1.33\delta r_c + 1.33\delta r_j + C \quad (C \text{ constant})$$

From the equation above, it is possible to see that the influences of relative deviations associated with  $r_c$  and  $r_j$  on spray nozzle flow amount changes are the same. However, when  $A > 2$  or  $A < 2$ , by contrast, the magnitudes of spray nozzle flow amount variation values produced by entry and exit aperture dimension variations are different.

#### 2.2.2 Influences of Relative Deviations Associated with Vortex Flow Chamber Radii $R_j$ on Spray Nozzle Flow Amounts

In conditions when  $r_j$ ,  $r_c$ ,  $\gamma$ ,  $\Delta p$  are constants, in order to analyze the influences of changes in vortex flow chamber radii  $R_j$  on spray nozzle flow amounts, at this time, it is possible to see that, when  $\delta R_j$  increase 1%, by contrast,  $\delta G$  drops  $n\%$ . At the same time, from Fig.2 curves, it is possible to see that, when  $A$  values increase,  $n$  also increases. Then, from equation (10), it is possible to know that  $\delta G$  follows increases in  $n\delta R_j$  and gets bigger.

Below, we take certain liquid rocket engine centrifugal type spray nozzles as examples and add explanations. One takes

$$r_c = 3.025^{+0.015}_{-0.015} \text{ mm}, r_j = 1.155^{+0.01}_{-0.01} \text{ mm}, R_j = 3.4 \pm 0.1 \text{ mm}, A = 3.6.$$

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The experimental operating medium is water. The water temperature variation range is  $10^\circ\text{C}$  to  $30^\circ\text{C}$  ( $\gamma_{10^\circ\text{C}} = 0.999 \text{ g/cm}^3$ ,  $\gamma_{30^\circ\text{C}} = 0.9957 \text{ g/cm}^3$ ).

Spray nozzle pressure drop  $\Delta p = 0.245 \pm 0.01$  MPa.

From  $A=3.6$ , one checks Fig.2 and gets  $n=0.76$ .

According to limit variation theory, in equation (10), the various parameter variations take the same sign. One then has

$$\delta G = (2-n)\delta r_e + 2n\delta r_i + n\delta R_j + \frac{1}{2}(\delta \gamma + \delta \Delta p)$$

Substituting data, calculations obtain:

$$\delta G = 0.00615 + 0.01316 + 0.0224 + 0.002 + 0.01 = 5.37\%$$

From the results above, it is possible to see that, with spray nozzle flow amount deviations caused by changes in various parameters at 5.37%, in this, changes associated with  $R_j$  account for 2.24%. Flow amount deviations created by changes in entry and exit aperture dimensions account respectively for 1.32% and 0.62%.  $\Delta p$  changes account for 1%. Deviations created in spray nozzle flow amounts by water temperature changes account for only 0.2%.

### 3 SPRAY NOZZLE FLOW AMOUNT DEVIATION CONTROL

From the analytical discussions above, it is possible to clearly reach the conclusion that relative deviations associated with spray nozzle vortex flow chamber radii  $R_j$  are key factors in causing changes in the flow amounts of the spray nozzles in question. To a very great degree, medium and small thrust liquid rocket engine dual component spray nozzles are appropriate for use. Because of working accuracies at the present time, deviations associated with the working of vortex flow chamber  $R_j$  ( $\pm 0.1$ mm) are much larger than the deviations ( $+0.01 \sim +0.015$ mm) associated with entry and exit apertures. How to control vortex flow chamber  $R_j$  dimension deviations, then becomes a key problem associated with controlling spray nozzle flow amount deviations.

$R_j$  sizes are determined by outer perimeter dimensions of spray nozzles. Vortex flow chamber  $R_j$  associated with medium and small thrust liquid rocket engine centrifugal type spray nozzles are generally relatively small.  $R_j$  dimension accuracy is limited by the means of working which currently exist. Various types of models of the same kind specify tolerance ranges which are  $\pm 0.1\text{mm}$ . Fig.3 shows situations in which, in working, tangential apertures created are not mutually tangent to vortex flow chamber walls as well as situations in which cuts in chamber walls form concave grooves. Fig.4 shows the flow state associated with liquid flowing along tangent direction apertures with wrong tangent levels and entering vortex flow chambers.

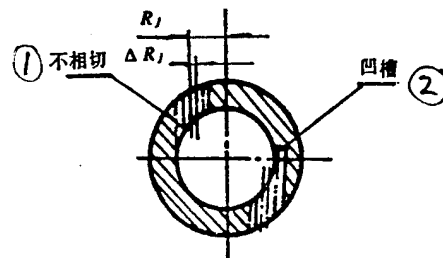


Fig.3

Key: (1) Not Mutually Tangent (2) Concave Groove

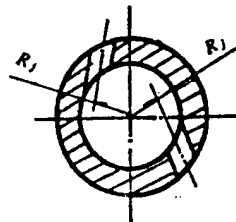


Fig.4

As far as the causes producing the working defects shown in Fig.3 are concerned, they are mainly that, due to the manufacturing precision of drilling tools for working tangent direction apertures not being high, or, because, during working processes, the gaps between drilling tools and the outer circumference of spray nozzle casings are excessively large, it makes--during drilling--drill heads get out of line. Because of this, the key is how to raise tangent direction aperture working quality.

### 3.1 Tangent Direction Aperture Centrifugal Type Spray Nozzle Water Test Results Associated with "Hollow Drilling Apertures" and "Solid Drilling Apertures"

There are many types of technical methods associated with working tangent direction apertures. Normally, tangent direction aperture working is carried out in a work sequence after spray nozzle vortex chamber (that is, spray nozzle inner cavity) working is completed. This is called "hollow aperture drilling". Another type is working tangent direction apertures in a work process before the working of vortex flow chambers. This is called "solid aperture drilling". See Fig.5.

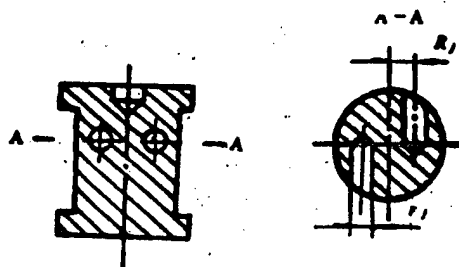


Fig.5

In Table 1, we set out tangent direction aperture centrifugal type spray nozzle water flow amount test measurement results associated with two types of test samples manufactured in

the two types of working methods above. Fig.6 and Fig.7 are dispersion rate curves associated with water flow amount numerical values for these two types of spray nozzle models.

### 3.2 Spray Nozzle Flow Amount Deviation Control

Water flow amount measurement results for test specimens worked with the two types of "hollow aperture drilling" and "solid aperture drilling" of tangent direction aperture centrifugal type spray nozzles described above clearly show that "hollow aperture drilling" spray nozzle flow amount dispersion rates reach 2.57%, and two sets of "solid aperture drilling" water flow amount dispersion rates are both relatively small. Tests clearly demonstrate that "solid aperture drilling" spray nozzle flow amount uniformity is superior to "hollow aperture drilling" spray nozzles.

TABLE 1

⑤							
① 加工方法	② 喷嘴主要几何尺寸			③ 试件数目 (个)	④ 喷嘴压降 $\Delta p$	⑤ 喷嘴水流量离散率 $\frac{\sigma}{\bar{x}} \times 100\%$	⑥ 流量分布频率图
	$d_s$ (mm)	$d_f$ (mm)	$R_f$ (mm)				
7 空心钻孔	6.05 $\pm$ 0.03	2.2 $\pm$ 0.02	3.4 $\pm$ 0.1	110	0.245 $\pm$ 0.01 MPa	2.57%	9 图 6
8 实心钻孔		2.2 $\pm$ 0.02		134		1.23%	9 图 7
		2.3 $\pm$ 0.02		139		1.68%	
10 注	$\bar{x}$ ——平均值 11 $\sigma$ ——均方根差 12						

Key: (1) Working Method (2) Key Spray Nozzle Geometric Dimensions (3) Test Item Number (single) (4) Spray Nozzle Pressure Drop (5) Spray Nozzle Water Flow Amount Dispersion Rate (6) Flow Rate Distribution Frequency Graph (7) Hollow Aperture Drilling (8) Solid Aperture Drilling (9) Fig. (10) Note (11) Average Value (12) Root Mean Square Error

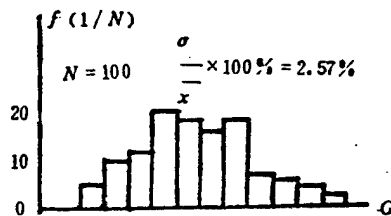


Fig.6

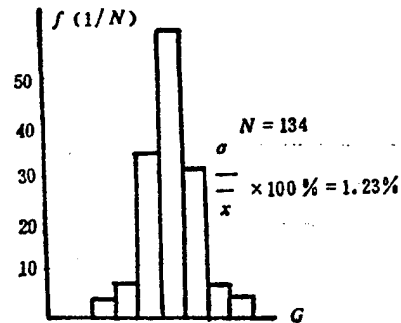


Fig.7

Introducing relevant materials, option is made for laser working of tangent direction apertures with good uniformity of worked holes. "As far as spray nozzles are concerned, the one iteration pass rate basically reaches 100%. Production efficiency can rise 10 fold." With regard to opting for the use of laser working of tangent direction apertures, there are clear effects on control of spray nozzle flow rate errors worth generalized application.

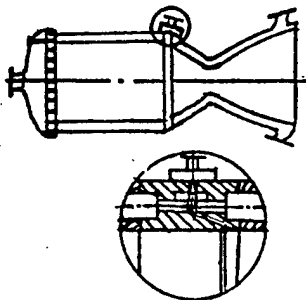
Above, we discussed key questions in liquid rocket engine head injector design technology. In a number of conventional combustion chamber injectors, cooling systems are generally set up in all the head side areas. Below are introduced trial results for a type of combustion chamber body interior cooling system superior to head interior cooling systems.

#### 4 ENGINES HAVING BODY INTERIOR COOLING SYSTEMS AS WELL AS BODY INTERIOR COOLING RING SYSTEMS

Development experience clearly shows that, as far as liquid rocket engine combustion chambers are concerned, only opting for the use of regeneration type cooling, it is difficult to realize reliable cooling. Moreover, when using interior cooling associated with single structures, the interior cooling flow amounts needed in order to form reliable cooling are relatively large. Relevant materials clearly indicate that, generally, they account for roughly 20% of the total engine fuel. In this way, engine specific thrust losses will be caused to increase.

In a number of liquid rocket engines, option it made for mixed types of cooling structures with cooling forms having body regenerative outer cooling and head inner cooling in a common structure. Where what this article introduces below is different from the type of structure above is its being a plan in which interior cooling systems are installed on combustion chamber convergence sections. See Fig.8. The key technology of the cooling plan in question is a type of interior cooling system form where fuel passes through slits and is supplied to the inner surfaces of hot combustion chamber walls to carry out cooling. This type of liquid film cooling, compared with low temperature gas wall protection layer cooling formed with head side area interior cooling systems has good results. At the same time, engine specific thrust losses given rise to because of structural interior cooling are reduced.

Fig.8



#### 4.1 Test Plans and Results

##### 4.1.1 Test Plans

Test engine A is a medium thrust liquid rocket engine with a pump pressure type delivery system and spontaneously combustible fuel (red fuming nitric acid and mixed amines). Test engine B opts for the use of test engine A's entire system of equipment, the same parameters, and the same test conditions for experiments. It only installs, on combustion chamber convergence sections, a "beveled slit type body interior cooling system".

Engine A and B interior cooling flow amount parameters are seen in Table 2.

TABLE 2

① 发动机	② 头部边区内冷却流量(kg/s)	③ 身部内冷却流量(kg/s)	
A	0.54	/	
B	0.20	0.15	0.13
④ 注: 内冷却燃料: 混胺-02 750			

(1) Engine (2) Head Side Area Interior Cooling Flow Amount  
(3) Body Interior Cooling Flow Amount (4) Note: Interior Cooling Fuel: Mixed Amine-02

##### 4.1.2 Thermal Test Run Results

Engine B--having body interior cooling systems for engine cooling--is reliable and structurally integrated. Parameters are coordinated, and performance, compared to engine A ground specific thrust, goes up 19.6 N\*s/kg. Key thermal test run data is presented in Table 3.

During development of a number of liquid rocket engines, one often encounters reliable cooling problems, associated with high component mixture ratios and large heat flow combustion chambers, which must be resolved. Results in opting for the use of body interior cooling systems can be seen from the preliminary research results.

#### 4.1.3 Body Interior Cooling Systems Associated with Drill Rod Welded Beveled Slit Type Integral Bodies

The special structural characteristic of this type of system is opting for the use of 80 exit apertures with 12° beveling angles. As far as firmly guaranteeing that liquid films and combustion chamber walls do not separate is concerned, liquid film adhesion is good. At the same time, in order to satisfy the liquid flow in beveled injection troughs having a certain initial momentum, the system has 24 small tangent direction apertures with 20°  $\phi 1.3$  angles of incline. After cooling agents pass through the angled tangent apertures and are rotated and accelerated, they then pass through bevels and are sprayed onto chamber walls.

Due to the need for manufacturing and working, rings associated with body interior cooling systems need to be divided into two interior and exterior rings. Moreover, to resolve a reliable connection of these two rings as well as a nondeforming integral body type structure is yet another key technology associated with the system in question. Going through tests of many plans, option was made for an integral drill rod welded plan, getting good results.

TABLE 3

	换算海平面比推力 (N·s/kg)	2) 内 冷 却 流 量 比 (%)		5 燃烧室效率	6 燃烧效率	7 喷嘴效率	试车时间 (s) 8
		3 总的内冷却流量/ 燃烧室总流量	4 身部内冷却流量/ 燃烧室总流量				
9 发动机 A11次平均值	2304.6	4	/	0.960	0.977	0.984	60.4
10 发动机 B 1#	2306.5	2.5	1.49	0.969	0.979	0.990	61.62
2#	2324.2	2.6	1.5	0.973	0.983	0.990	61.6

Key: (1) Converted Sea Level Specific Thrust (2) Interior Cooling Flow Amount Ratios (%) (3) Total Interior Cooling Flow Amount/Combustion Chamber Total Flow Amount (4) Body Interior Cooling Flow Amount/Combustion Chamber Total Flow Amount (5) Combustion Chamber Efficiency (6) Combustion Efficiency (7) Jet Tube Efficiency (8) Test Run Time (9) Average Values for 11 Engine A Iterations (10) Engine B

#### 4.2 Integral Body Drill Rod Welded Plan

Liquid flow test results for beveled slit type drill rod welded integral structure body interior cooling systems clearly show that liquid film homogeneity, stability, and wall adhesion characteristics are good.

After engine thermal test runs, combustion chambers once again carry out liquid flow tests. Results clearly show that there are no changes in body interior cooling system liquid flows before and after thermal test runs. This, then, goes a step further to explain such characteristics as reliable and stable performance of the system structures in question.

As far as body interior cooling rings with diameters of 190mm are concerned, at the present time, we still have not found similar products. With regard to the clearly good cooling

results that the interior cooling systems in question get in medium thrust liquid rocket engines, the unit circumference interior flow amount is barely  $2 \sim 2.5\text{g/s}$ . Initial research results in this area show that its development has a future.

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